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A KINEMATIC MODEL FOR PREDICTING THE EFFECTS OF HELMET MOUNTED SYSTEMS[1]

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SUMMARY

A statistical study was made using head kinematic response data from a set of 79 human -X impact acceleration tests conducted at the Naval Biodynamics Laboratory. Five volunteer[2] subjects were tested successively in three configurations: (a) no helmet, (b) helmet only, and (c) helmet with weights. The peak acceleration levels ranged from 3g to 10g. Three kinematic responses, the X and Z components of the linear acceleration and the Y axis angular acceleration, were analysed. These acceleration curves were fitted with polynomial splines using least squares techniques. The fitted peaks and times to peak were then regressed against sled acceleration, initial head orientation and head/neck anthropometric parameters. Statistical measures of goodness of fit were highly significant. The regression equations were used to simulate the effects of varying individual parameters (such as total head mass, peak sled acceleration, neck length, etc.).

The results demonstrate an analytical approach for extrapolating human head/neck kinematics to levels and types of exposure where injury would be expected. Future applications of this modeling technique include analysis of the effects of mass distribution parameters on head/neck dynamic response to +Z vertical impact acceleration.

LIST OF SYMBOLS

AAX X-component of head linear acceleration in the sled coordinate system (m/sec^2)
AAZ Z-component of head linear acceleration in the sled coordinate system (m/sec^2)
DOP duration of peak sled acceleration (msec)
ESV endstroke sled velocity (m/sec)
HM total head mass. Includes head, mouth instrumentation, and helmet configuration mass (kg)
HO helmet only configuration
HW helmet with weights configuration
IDAX initial X-component of head linear displacement in the sled coordinate system (m)
IDAZ initial Z-component of head linear displacement in the sled coordinate system (m)
INT intercept of a regression line
IPHB initial head angular displacement about Y-axis of head anatomical coordinate system (rad)
NC neck circumference (cm)
NL neck length (cm)
NH no helmet configuration
PSA peak sled acceleration (m/sec^2)
QHB head angular acceleration about Y-axis of head anatomical coordinate system (rad/sec^2)
ROO rate of sled acceleration onset (m/sec^3)

INTRODUCTION

Current aviator helmet developments, which incorporate a variety of helmet mounted protective and weapons related systems including night vision goggles, may compromise aircrew safety. As part of a long-term program to develop criteria for protecting aircrew from the potentially harmful effects of impact acceleration, the Naval Biodynamics Laboratory (NAVBIODYNLAB) is studying human head and neck response to whole-body acceleration to develop predictive models for neck injury.

The regression model reported here can be used to simulate the effects of changes in acceleration profile, mass distribution properties of the head, and varying neck morphology on human head/neck kinematics. Such models allow study of the individual effects of varying parameters (such as head mass) whose experimental measurement might compromise the safety of the volunteers and would require excessive amounts of data. In particular, this paper describes a predictive regression model for unhelmeted and helmeted human head kinematics for the -X vector direction.

METHODOLOGY

(1) Database. The data used in this analysis were obtained from 79 -Gx impact acceleration experiments involving five human research volunteers (HRVs) [Table 1].

Table 1. Test Matrix of Peak Sled Acceleration by Helmet Configuration

Conditions	Subject ID				
	H166	H168	H169	H172	H175
NH 3g	1	1	2	1	1
HO 3g	1	1	1	1	1
HW 3g	1	1	1	1	1
NH 5g	1	1	1	1	1
HO 5g	1	1	1	1	1
HW 5g	1	1	1	1	1
NH 7g	1	1	1	1	1
HO 7g	1	1	1	-	1
HW 7g	-	1	1	-	1
NH 8g	1	2	1	1	1
HO 8g	1	2	2	-	1
HW 8g	-	2	2	-	-
NH 9g	1	1	1	1	1
HO 9g	1	1	1	-	1
HW 9g	-	-	-	-	-
NH 10g	3	3	2	1	3

Number of runs at each configuration and g-level.

[1] The interpretations and opinions in this work are the authors' and do not necessarily reflect the policy and views of the Navy or other government agencies.

[2] Volunteer subjects were recruited, evaluated, and employed in accordance with procedures specified in the Department of Defense Directive 3216.2 and Secretary of the Navy Instruction 3900.39 series. These instructions meet or exceed prevailing national and international standards for the protection of human subjects.

All experiments were conducted at the NAVBIODYNLAB. The experimental and instrumentation details have been extensively reported elsewhere [1-5]. The HRVs were instrumented to measure head and neck displacement and linear and angular acceleration. They were seated with full torso restraint and the head and neck were allowed to move freely. Each volunteer was tested successively in three configurations: (a) no mass addition; (b) helmet and weight-carrier; (c) helmet, weight-carrier, and two pairs of .213 kg weights mounted symmetrically, mid-sagittally high in front. A progression of increasing sled accelerations from 3g to 10g was completed for each configuration.

Figure 1 illustrates typical acceleration time traces for 5g to 10g. The identified parameters include peak sled acceleration (PSA), endstroke sled velocity (ESV), rate of acceleration onset (ROO), and duration of peak acceleration (DOP) [Table 2].

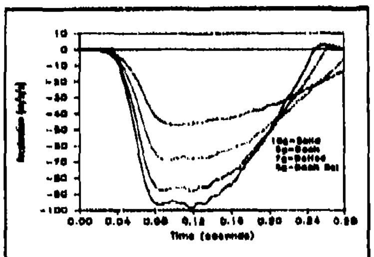

Figure 1. Typical sled acceleration profiles.

Table 2. Range of Sled Acceleration Parameters

Variable	Units	Range
PSA	m/sec^2	28.9 - 98.7
ESV	m/sec	5.5 - 13.8
ROO	m/sec^3	519 - 2679
DOP	msec	128 - 104.2

The selected initial position parameters are the initial head linear displacements IDAX and IDAZ and the initial head angular displacement IPHB [Table 3]. These positions are measured with respect to the origin of the sled coordinate system. All tests were run in the nominal neck-up, chin-up (NUCU) condition with IPHB expected to be close to zero radians. Within-subject ranges for the position parameters were much narrower than the overall range of variation.

Table 3. Range of Initial Head Linear and Angular Displacements

Variable	Units	Range
IDAX	meters	-1.332 - -1.243
IDAZ	meters	1.503 - 1.667
IPHB	radians	-.349 - -.025

The identified head/neck anthropometry parameters are head mass, neck length, and neck circumference. Head length and circumference are measured as indicated in Figures 2 and 3. Neck circumference is measured as in Figure 4. However, neck length is computed as the difference between (T1-top of head) and head height as indicated in Figures 5 and 6.

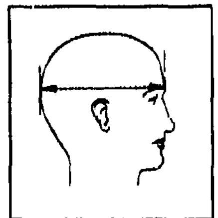

Figure 2.

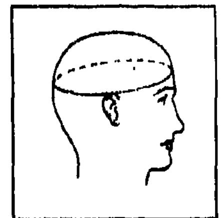

Figure 3.

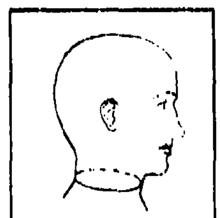

Figure 4.

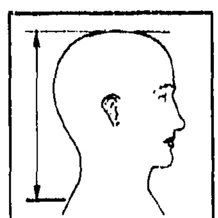

Figure 5.

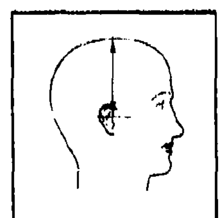

Figure 6.

Head mass for the un-instrumented HRVs were estimated using the formula [6]:

$$HM = .21618\ HC - .12184\ HL - 5.5936$$

where:
- HM = head mass (kg)
- HC = head circumference (cm)
- HL = head length (cm)

The measurements for each HRV are listed in Table 4.

Table 4. Selected Head and Neck Anthropometric Data on Five Volunteer Subjects

Subject	Head Length (cm)	Head Circum. (cm)	Head Mass (kg)
H166	20.1	56.5	4.172
H168	21.1	58.9	4.569
H169	19.5	57.0	4.353
H172	19.6	57.8	4.513
H175	19.6	56.6	4.266

Subject	T-1/Top of Head (cm)	Head Height (cm)	Neck Length (cm)	Neck Circum. (cm)
H166	27.3	13.4	13.4	36.3
H168	26.4	13.9	12.5	39.0
H169	26.7	13.2	13.5	38.0
H172	27.9	12.6	15.1	36.9
H175	27.3	12.4	14.9	37.2

The added head mass for each subject for each configuration is shown in Table 5. The added mass in the unhelmeted case consists of the mouth mount, T-plate and connecting straps. The shifts in the X and Z components of the center-of-gravity (c.g.) are with respect to the c.g. taken from cadaver data [11]. The shift in the Y component of the c.g. is negligible, due to the lateral symmetry of the total head mass.

Table 5. Added Head Mass and Shift in c.g. for Each Subject for Each Configuration

Subject	NH (kg)	c.g. shift (cm)	HO (kg)	c.g. shift (cm)	HV (kg)	c.g. shift (cm)
H166	0.493	1.0, -0.8	0.883	1.0, -0.1	1.035	1.9, 1.0
H168	0.477	1.0, -0.8	0.996	1.0, -0.1	1.016	2.0, 1.0
H169	0.474	1.0, -0.7	0.885	1.0, 0.1	1.077	1.9, 1.1
H172	0.486	1.0, -0.8	1.031	1.0, -0.1	1.073	2.1, 0.7
H175	0.483	1.1, -0.7	0.883	1.2, -0.1	1.745	2.3, 0.7

(2) Analysis. To smooth the data, the head linear and angular acceleration curves (AAX, AAZ, and QHB) were fitted with polynomial splines using least squares techniques [7, 8, 9]. For each curve, the times to peak and peak amplitudes for the first five peaks were determined from the fitted curve (Figure 7).

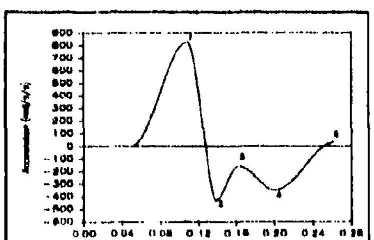

Figure 7. The five chosen peaks for QHB.

These computed values were then regressed against the four sled parameters (PSA, ESV, ROO, DOP), the initial head orientation in the X-Z plane (IDAX, IDAZ, IPHB) and several functions of three anthropometric parameters (head mass, neck length, neck circumference) to obtain a prediction model for peak values for each curve. Several SAS® regression programs (STEPWISE, RSQUARE, REG) were used in the parameter selection process.[3] A simulation model was developed by adding appropriate normally distributed errors to the prediction model. The predicted curves are obtained by fitting the predicted peak values with cubic splines. Estimated upper and lower confidence bands for each curve were generated by simulating the predicted curve 100 times and determining the upper and lower boundaries.

RESULTS

The regression models for the peak values and times to peak for the three kinematic parameters are listed in Appendix I. Figures 8 - 10 illustrate the estimated confidence bands for the three kinematic curves for test LX5460. Figures 11 - 13 illustrate the effect of varying only the acceleration profile parameters. PSA and ESV were the parameters perturbed in the simulations since they were the sole acceleration profile parameters appearing in the various regression models. As expected, peak magnitudes increase and times to peak decrease with increased PSA and ESV for all three kinematic responses.

Figures 14 - 15 illustrate the effect on AAZ of varying added head mass from 0.0 kg to 3.0 kg at 8g and 16g respectively. Figures 16 - 17 illustrate the same effect on angular acceleration, QHB. There is no statistically significant effect on AAX due to head mass. These effects are small. The decrease in peak head acceleration is only 7 m/s^2 and 50 rad/s^2 for each additional kg of added mass. The effects of the input acceleration (PSA) are much greater than these small effects as illustrated in Figures 18 - 21.

Figure 18 shows that a 1g increase in PSA almost cancels the effect of a 2 kg increase in added mass. These opposing effects are illustrated in Figure 19 which shows that a .5g increase in PSA cancels the opposing effect of a 1 kg addition to head mass. These effects for head linear acceleration also hold true for angular acceleration (Figures 20 - 21).

Regarding neck anthropometry, peak magnitudes of head acceleration decrease with increasing neck circumference and increasing neck length. Because of the narrow range of neck anthropometry represented by the five subjects, no general conclusions can be drawn. However, these two neck anthropometry parameters do contribute significantly to the predictive model adding from 6 to 10 percent of R^2 in some cases [10].

[3] SAS Institute, Inc., SAS/STAT®, Release 6.03.

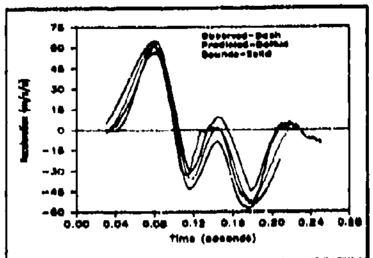

Figure 8. AAX simulation of 8g test.

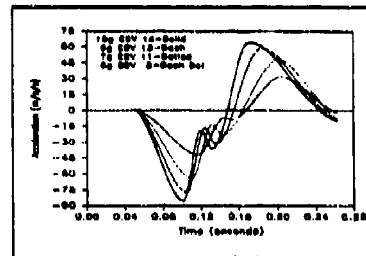

Figure 12. Effect of PSA and ESV on AAZ.

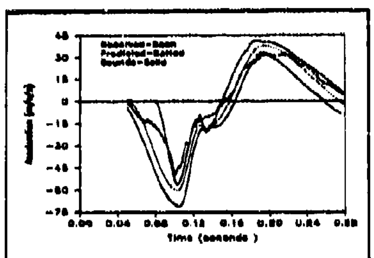

Figure 9. AAZ simulation of 8g test.

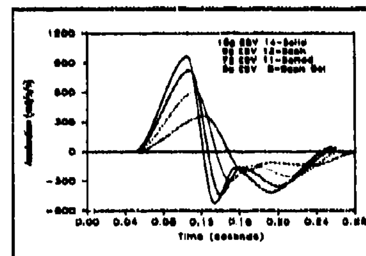

Figure 13. Effect of PSA and ESV on QHB.

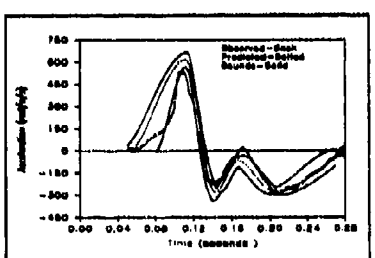

Figure 10. QHB simulation of 8g test.

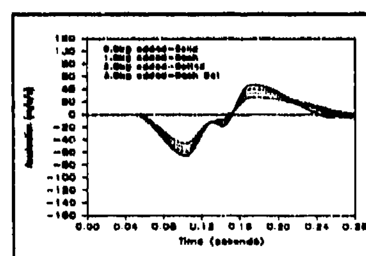

Figure 14. Effect of added mass on AAZ at 8G.

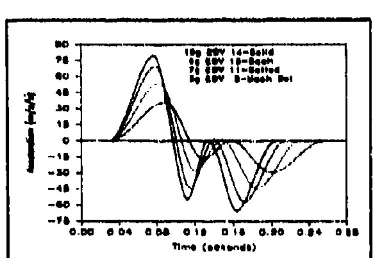

Figure 11. Effect of PSA and ESV on AAX.

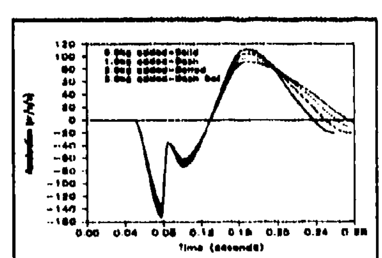

Figure 15. Effect of added mass of AAZ at 16g.

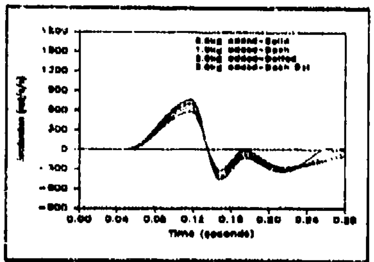

Figure 16. Effect of added mass on QHB at 8g.

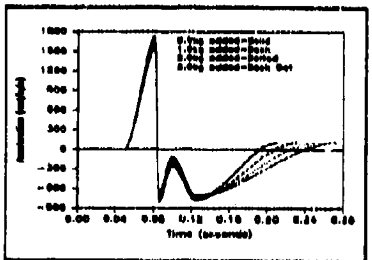

Figure 17. Effect of added mass on QHB at 16g.

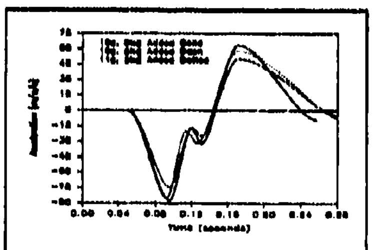

Figure 18. Relative effect of PSA and added head mass on AAZ (10g, 0kg base level).

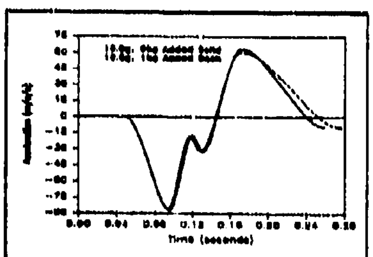

Figure 19. Combinations of PSA and added head mass yielding equivalent AAZ.

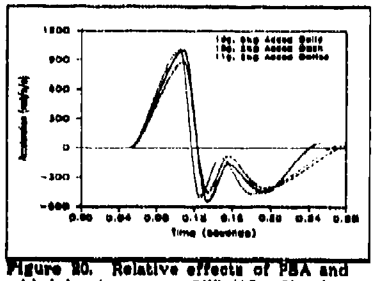

Figure 20. Relative effects of PSA and added head mass on QHB (10g, 0kg base level).

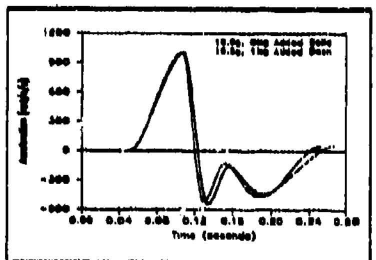

Figure 21. Combinations of PSA and added head mass yielding equivalent QHB

DISCUSSION AND CONCLUSIONS

The results of this study provide an analytical approach to extrapolating helmeted human volunteer head/neck kinematics to levels where injury might be expected. A single analytic model describes both helmeted and unhelmeted kinematics with total head mass being the sole head inertial parameter required. Based on this model, added head mass reduces peak head linear and angular acceleration for -Gx. This reduces the increase in the estimated forces and torques at the occipital condyles [8] due to this added mass. Analysis of these interacting effects requires more detailed models.

Future models will incorporate all the various head inertial parameters (center of gravity, moments, etc.) among the independent regression variables. The influence of neck anthropometry on head kinematics will also be incorporated, using a greater range of data.

The basis for this model development is the +Z vertical helmeted test series presently underway at NAVBIODYNLAB. Twelve subjects are being tested under nine different mass addition treatments at levels ranging from 3 to 8g's. The range of acceleration profile, head mass distribution, and neck anthropometry parameters covered by this series will yield a definitive regression model for human +Z helmeted head kinematics. This model can be used to analytically validate anthropomorphic manikins, to check biomechanical models of human response to +Z impact acceleration with various helmet mounted devices, and to help establish tolerance limits for inertial loading due to such systems.

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APPENDIX I: Regression Tables

AAX TABLE

	INT	PSA	ESV	NC	NL	NL^2	NL^3
P1	21424	.87		-282	-465951	3384003	-8169786
P2		-1.54	7.04				
P3	-176			466			
P4	-27563	-.71			612667	-4523065	11092403
P5	-.70						

	INT	PSA	ESV	NC	NL	NL^2	NL^3
T1	5.38		-.0020	-.1348	-114	820	-1969
T2	.16		-.0031				2
T3	.08	-.0004		.2671			
T4		-.0007		.5352			6
T5	.45		-.0091	.5638		-58	294

AAZ TABLE

	INT	ESV	IDAX	IPHB	HM	NC	NL	NL^2
P1	-156	-8			6	401		
P2		-2	-66	39		-172		
P3	-1450	-6	108	39	4		23647	-86626
P4		6	-117		-7		-1956	7162
P5	11	-1						

	INT	PSA	ESV	IDAX	IPHB	HM	NL
T1		-.0003		-.0996	-.0245		
T2	.1789		-.0042				
T3	.1626		-.0037				
T4	.1309	-.0029	.0206				.3387
T5						.0186	1.3636

QHB TABLE

	INT	PSA	ESV	IDAX	IDAZ	IPHB	HM	NC	NL	NL^2	NL^3
P1	590152	12			-3383		-59	4481	-12776351	93057980	-225326898
P2	-3282	-14	66		1945		46				
P3	-2514		-10	-427	1167	180	41				
P4	1220	-6		984		-178	20				
P5	-1628		0		1176	191					

	INT	ESV	IDAX	IDAZ	HM	NC	NL^3
T1	.3268	-.0033	-.0999	-.1949			
T2	.2034	-.0056					0
T3	.2467	-.0065					
T4		-.0081				.6826	18
T5	.1946	-.0049			.0201		18